Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 5 (2010) 703–712

Physics Procedia

www.elsevier.com/locate/procedia

LANE 2010

Multi-species detection with dual-pump-CARS: Possibilities and limitations

S.C. Eichmann[a,b,*], Y. Gao[a,b], M.C.Weikl[c], F. Beyrau[d], T. Seeger[a,b], A. Leipertz [a,b]

[a]*Lehrstuhl für Technische Thermodynamik (LTT), Friedrich-Alexander-Universität Erlangen-Nürnberg, Am Weichselgarten 8, 91058 Erlangen, Germany*

[b]*Erlangen Graduate School in Advanced Optical Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Paul-Gordan-Str. 6, 91058 Erlangen*

[c]*Now with: Linde Engineering, Pullach, Germany*

Now with: [d]*Department of Mechanical Engineering, Imperial College London, London, UK*

Abstract

Dual-pump coherent anti-Stokes Raman scattering is a promising measurement technique which can be used for combined temperature and multi-species detection in combustion diagnostics. Its application is demonstrated in various flames using different fuels often used as a reference in research laboratories. By means of these examples, the potential and limitations of dual-pump-CARS in combustion processes will be discussed.

Keywords: Dual-pump CARS, combustion research, concentration measurements, major and intermediate species detection, sooting flames

1. Introduction

For an understanding and further improvement of combustion processes a detailed knowledge of the complex interactions of chemistry, fluid dynamics and heat and mass transport phenomena is necessary. Therefore local gas temperatures and species concentration information is of utmost importance. There are different optical techniques capable to measure species concentration and temperature information (see e.g. Eckbreth [1]). One well accepted optical technique for the investigation of combustion processes is coherent anti-Stokes Raman scattering (CARS), which is divided in rotational CARS (RCARS) and vibrational CARS (VCARS). In both cases Raman transitions are excited resonantly by the difference frequency of two lasers. A third narrowband probe laser beam is scattered from the excited Raman coherence, and the signal is emitted as a coherent beam that is Raman shifted to the anti-Stokes side of the probe.

* Corresponding author. Tel.: +49-9131-8529767; fax: +49-9131-8529901.
E-mail address: simone.eichmann@ltt.uni-erlangen.de.

1875-3892
doi:10.1016/j.phpro.2010.08.102

With rotational CARS (RCARS), Raman transitions of almost all combustion relevant molecules can be probed simultaneously using one single broadband laser. This is possible as most of the rotational Raman transition states are in the region of about 250 cm^{-1}. However, with increasing number of detected molecules the RCARS-spectra of the different molecules overlap and evaluation gets rather complex. In standard VCARS, multi-species detection is very limited because the vibrational transitions of most molecules are widely spread. For the most relevant molecules in combustion processes, the vibrational energy levels depart from the exciting frequency in a range approximately between 500 cm^{-1} and 4200 cm^{-1} and only a few spectrally close molecule combinations like N_2 and CO or CO_2 and O_2 are possible to detect simultaneously. One promising approach for the simultaneous temperature and multi-species measurements is the dual-pump-CARS (DP-CARS) technique, where in contrast to standard VCARS a second narrowband laser source as either a fixed-frequency source or a tunable dye laser is used to excite two spectral regions simultaneously via the difference frequencies ω_1-ω_S and ω_2-ω_S. The applicability as well as the limitations of this technique for combustion diagnostics will be demonstrated at ambient pressure at different flames often used as a reference in different laboratories.

Beside gas temperatures a typical information needed in combustion research is the time resolved local fuel-air ratio. This knowledge is essential to understand the injection and mixing process in order to develop efficient low emission combustion systems like gas turbines as well as internal combustion engines. In principle, Raman spectroscopic techniques are ideally suited for such investigations since the Raman spectrum is sensitive to changes both in temperature and in concentration. Vibrational linear Raman spectroscopy (LRS) has been used in numerous applications for the detection of almost all major species in combustion environments [1-5]. However, its applicability for single-pulse thermometry is limited because the signals of the spontaneous Raman spectroscopy process are comparatively small. In this case DP-CARS is a favorable technique which is demonstrated by simultaneous temperature and fuel-air ratio measurements in an ethene-air flame. The possibility to extend this to even more complex fuels like isooctane, n-hexane or methanol is discussed.

To get a fully understanding of the complex mechanism of combustion not only the concentration of fuel and air but also the concentration of intermediate species like CO and H_2 is of great importance. These intermediate species are e. g. produced in fuel rich combustion situations present in partially premixed hydrocarbon fueled flames. In this case the detection of CO by LRS is suffering from C_2 interferences [6]. In contrast to that, DP-CARS can be used in partially premixed flames without a significant influence of interfering fluorescence signals. In addition also H_2 is accessible by DP-CARS either by probing the S(5) and S(6) H_2 transition [7, 8] or the Q-branch transitions of H_2 [9]. The first approach is favorable in H_2-fueled flames but it is not suitable for low H_2 concentrations present in hydrocarbon fueled flames. Nevertheless for the evaluation of such spectra, line width models are necessary to calculate theoretical spectra which are then compared with experimental ones. Therefore a new line width model taking N_2-H_2 collisions into account was used for a simultaneous temperature, concentration measurement of CO and H_2 in a partially premixed propane-air flame.

Beside this the mechanism of soot growth and oxidation is an important issue in combustion diagnostics. One import parameter influencing soot growth and oxidation is the local gas temperature. In highly sooting fuel-rich premixed or diffusion flames LRS even for gas temperature measurements might no longer be applicable due to strong PAH fluorescence signals [10]. Also the standard VCARS signal is affected by the soot, because the signal is occuring at 473 nm and is therefore interfering with the C_2 Swan band. Different approaches were proposed to overcome this effect. Jonuscheit et al. [11] fitted only the undisturbed areas of N_2 spectra and compared it with evaluations of the complete N_2 spectra. However, a clear difference of about 70°C between both evaluation procedures even in the non-sooting areas was observed. A more suitable possibility is to shift the signal to an interference free region. This can be done e. g. by the use of a narrowband dye laser as pump laser [12] or by DP-CARS. The potential of DP-CARS in such a harsh environment is demonstrated.

2. Dual-Pump-CARS Technique

The basic principles of DP-CARS are described elsewhere [13] and therefore only a short explanation shall be given here. A dual-pump CARS setup consists essentially of three lasers, two narrowband and one broadband laser. One of the narrowband lasers is a solid-state laser, i.e., a frequency-doubled Nd:YAG laser (ω_1) with a fixed emission wavelength of 532 nm. The second narrowband laser is commonly a tunable dye laser (ω_2). For the

generation of signals from two different molecules the frequency difference of each pump laser and the broadband dye laser (ω_S) has to coincide with the Raman transition. Hence in general two combinations are possible and to simplify the setup a combination is chosen, that both dye lasers can be pumped with visible radiation of the Nd:YAG laser:

$$\omega_1 - \omega_S = \Delta\omega_{Species1} \;,\; \omega_2 - \omega_S = \Delta\omega_{Species2} \quad (1)$$

$$\omega_1 - \omega_S = \Delta\omega_{Species2} \;,\; \omega_2 - \omega_S = \Delta\omega_{Species1} \quad (2)$$

This is shown schematically in the energy diagram in Fig. 1. The CARS-signals of the two spectral regions are generated simultaneously and are only slightly tuned within the range of the broadband dye laser. As a result, they can be detected by the use of one spectrometer and one CCD-camera.

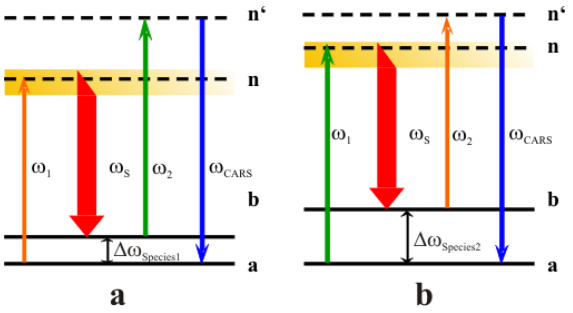

Fig. 1. Energy diagram of DP-CARS process

Depending on the molecule combinations of interest and on the according Raman transition the wavelength of the narrowband and broadband dye laser was selected. In Table 1, a few examples for possible molecule combinations and the corresponding laser wavelengths are given.

Table 1. Possible molecule combinations and corresponding laser wavelength

molecule combination	1. pump beam	2. pump beam	stokes beam	Reference
N_2, CH_4	532 nm	549 nm	630 nm	[14]
N_2, C_3H_8	532 nm	555 nm	607 nm	[15]
N_2, O_2, H_2	532 nm	554 nm	607 nm	[16]
N_2, O_2, CO	532 nm	552 nm	602 nm	[13]

A schematic drawing of a dual-pump-setup is shown in Fig. 2. The frequency-doubled radiation from a Nd:YAG laser provides the pump beams for the CARS process and for the two dye lasers. Part of the Nd:YAG laser pulse was split off to pump a narrowband dye laser. This laser acts as a second pump laser (ω_2). The polarization of all beams were aligned in vertical direction and controlled with polarizing prisms (GP). Each beam diameter is adjusted by the use of a telescope (T). A $f = 300$ mm lens was used to focus the beams in a planar BOXCARS arrangement resulting in a probe volume of 1.7 mm in length and 0.1 mm in diameter. The probe volume was measured by moving a glass microscope slide along the measurement volume and recording the non-resonant CARS signal. Using a series of dichroic mirrors, the signal was spectrally separated from the remaining pump beam and focused into the spectrometer equipped with a CCD-camera.

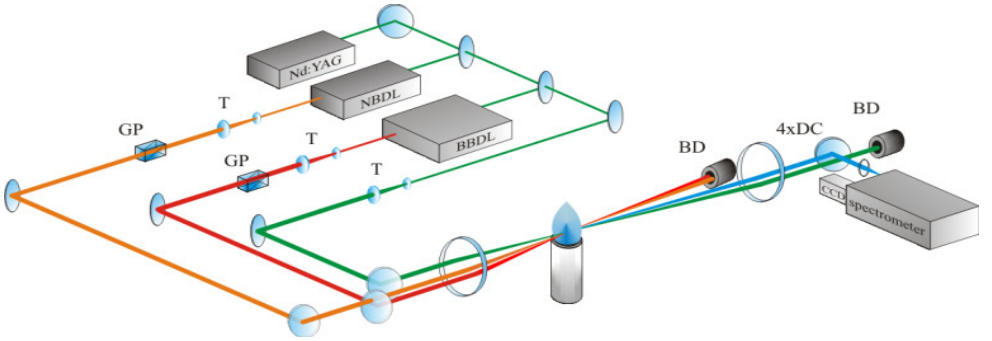

Fig. 2. DP-CARS set-up

3. Major Species Detection

By detecting the DP-CARS signals of the major species N_2, O_2 and C_2H_4 temperature and fuel-air ratio can be determined simultaneously. As an example DP-CARS is applied in a premixed C_2H_4 flame established on a Wolfhard Parker burner [17]. For this experiment, a frequency-doubled Nd:YAG laser (10Hz, 10 ns) with a band width of 0.5 cm^{-1} and a narrowband dye laser with a wavelength of 551 nm and a band width of 0.1 cm^{-1} were used as pump lasers. As Stokes laser, a broadband dye laser with maximum intensity at 605 nm and a band width of ~250 cm^{-1} (FWHM) was used. With this system, N_2 ($\tilde{\nu}_1$ = 2331 cm^{-1}), O_2 ($\tilde{\nu}_1$ = 1556 cm^{-1}) and the ν_2 transition of C_2H_4 ($\tilde{\nu}_1$ = 1623 cm^{-1}) can be probed simultaneously. Temperature information was achieved by the spectral shape of the nitrogen signal. For the evaluation of O_2 and N_2, the measured data were obtained from a least-squares fitting procedure against library of theoretical calculated spectra. The spectra were calculated by an in house-written computer code using the modified exponential gap law (MEG) [18]. For the C_2H_4 concentration, calibrations measurements were performed with three different mixtures of nitrogen and C_2H_4 in a heated cell equipped with a Ni-Cr-Ni thermocouple. The temperature inaccuracy was less than 5K. The mixtures were produced gravimetrically with an inaccuracy less than 0.5%. Measurements were performed at a fuel-air ratio of Φ = 2. The standard deviations are 6.8% for O_2 and 5.5% for C_2H_4. Measurements were taken at 1 mm, 10 mm, 19 mm, 28 mm and 37 mm downstream position as indicated in the photo in Fig. 3a. Only at a downstream position of 1 mm, fuel could be detected. Results of concentration and temperature profiles at this position are shown in Fig. 3b starting in the centre of the burner. The temperature profile indicates clearly the location of the flame front. Fuel and oxygen concentration have a maximum in the centre of the burner at zero mm and are decreasing towards the flame front. In the combustion zone, both concentrations become zero and outside the flame, only oxygen is observed.

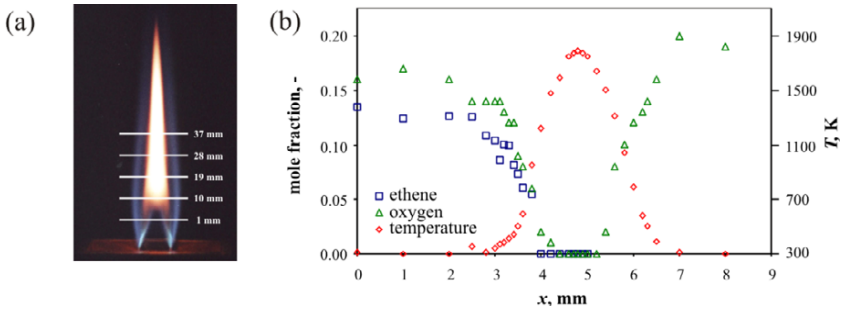

Fig. 3. Temperature and concentration results at 1 mm downstream position (a), photo of the flame (b)

Besides rather simple molecules like C_2H_4 and O_2, this technique offers the opportunity to probe also more complex fuels. For this approach the spectral region of about 2900 cm^{-1} was used, because the vibrational transition of the CH-bonding of most hydrocarbon fuels are within in this spectral region. Hydrocarbon based fuels are rather complex and the corresponding CARS spectra are still difficult to calculate. Nevertheless, data evaluation is possible by using CARS spectra achieved in a calibration cell. In Fig. 4 spectra from different fuel/nitrogen mixtures are shown. Fig. 4a-c show n-hexane/nitrogen spectra for equivalence ratios between 1.02 and 3.00 at ambient pressure and room temperature. For nearly stochiometric conditions, the n-hexane CARS signal is nearly not noticeable. For higher fuel concentrations, the signal of n-hexane signal can be seen clearly, but still for the rich combustion situation (Φ=3.0) the n-hexane signal is one magnitude lower compared to the nitrogen signal intensity. Isooctane (see Fig. 4d) and a multi-component fuel (see Fig. 4e) similar to natural gas show a similar behavior. This may result into problems due to the limited dynamic range of the detector. In this case the dynamic range of the measurement can be extended by tuning the broadband Stokes laser so that the spectral intensity is higher for the species that has the lesser concentration [15]. Another possibility is to use a polarization approach to adjust the relative intensity of the two CARS signals [19]. For the nitrogen/methanol mixture (Φ = 3.0) the situation is different. Here the spectral intensities of both DP-CARS signals are in the same order of magnitude as shown in Fig. 4f. Large variations in the gas concentration especially for high pressure applications may also lead to a strong, varying background from nonresonant four-wave mixing coherently interferes with the resonant DP-CARS signal. The nonresonant interference can be suppressed by selecting appropriate polarizations for the incoming beams [1, 20].

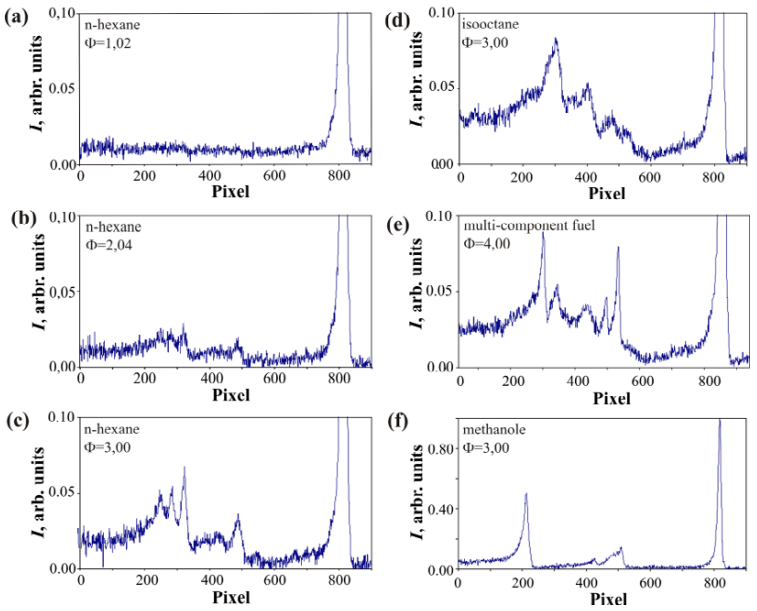

Fig. 4. DP-CARS spectra of different nitrogen/fuel mixtures

4. Intermediate Species Detection

Partially premixed flames are numerous in practice, from the very simple domestic gas burners to highly complex phenomena in automotive direct-injection engines. In such flames, beside temperature intermediate species like H_2 and CO play an important role in the ongoing chemistry. Using a dual-pump CARS setup N_2, H_2 (Q-branch) and CO are accessible. In order to enhance the H_2 accuracy for measurements at ambient pressure a new line width model (KS-3D model) is implemented in the evaluation code [21]. As pump beams, a seeded, frequency doubled Nd:YAG laser (10Hz, 10 ns) with a band width of 0.003 nm and a narrowband dye laser with a wavelength of

593.9 nm and a band width of 0.03 nm were used. As Stokes laser, a broadband dye laser with a band width of 250 cm^{-1} (FWHM) and a wavelength centered at 680 nm was used. With this combination, N_2 ($\tilde{\nu}_1 = 2331\ cm^{-1}$), CO ($\tilde{\nu}_1 = 2145\ cm^{-1}$) and H_2 ($\tilde{\nu}_1 = 4166 cm^{-1}$) were detected.

Flame measurements in were obtained in a partially premixed Bunsen type propane-air flame, consisting of two coaxial tubes of 12 and 51 mm diameter. At ambient pressure, a mixture of synthetic air (80% N_2, 20% O_2) and propane with an equivalence ratio of $\Phi = 1.90$ was used. The flame was stabilized by co-flow air with a flow rate of 32 sl/min to adjust an inner flame height of 50 mm. A photo of the flame is shown in Figure 5a. A double-flame structure typical for partial premixed flames can be observed consisting of a clearly visible premixed inner flame surrounded by a non-premixed flame. At the tip of the inner flame front yellow blackbody radiation indicates the occurrence of soot. A typical DP-CARS spectrum taken in the inner flame front at a height h = 15 mm is shown in Figure 5b. The CARS signal of the H_2 Q-branch is clearly visible. The CO signal however is rather weak and is shown more clearly in the inset. Good agreement was found between measurement and calculation. Only for the Q (5) line of hydrogen, a noticeable discrepancy was found which can be contributed to the procedure in including the Herman-Walli factor [22].

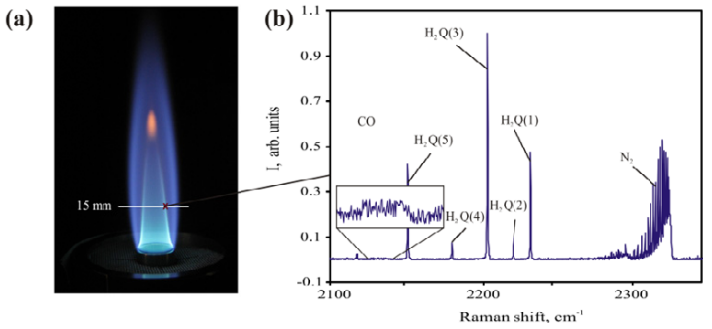

Fig. 5. Spectrum taken n in the inner flame front at h = 15 mm

Temperature results at a constant height of 15 mm above the burner exit along a line using the whole DP-CARS spectrum are compared to results achieved by the well established N_2-Q-branch thermometry. Both temperature results are shown Figure 6 together with H_2 concentrations measured by DP-CARS. Because H_2 is intermediate specie, only the region around the inner flame front is considered. For each measurement point, the mean values for temperature are plotted. The temperature evaluated with the KS-3D model is very close to the N_2 CARS temperature even in the region where a considerable amount of H_2 is present.

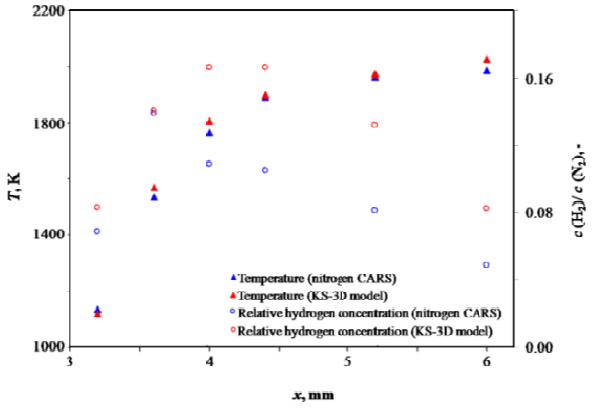

Fig. 6. Temperature a nd concentration profiles crossing the inner flame front evaluated with the KS-3D model in comparison to N_2 CARS thermometry

5. Application in harsh environment

Highly sooting fuel-rich premixed or diffusion flames are challenging for laser based diagnostic techniques. Even the use of standard VCARS is limited in fuel-rich hydrocarbon flames [23] because the Swan transition $A3\pi_g$–$X'3\pi_u$ at 473.7 nm occurs in the same spectral region as the N_2 CARS signal (see Fig. 7). This problem can be avoided successfully by shifting the signal into a spectral region that is not affected from absorption/emission bands from the C_2 radicals. From Fig. 7, it can be seen that there are generally different possibilities to shift the signal. First, pure rotational Raman transitions of nitrogen can be probed (RCARS), second the wavelength of the second pump laser can be changed (DP-CARS) and third all laser wavelengths can be changed (shifted VCARS).

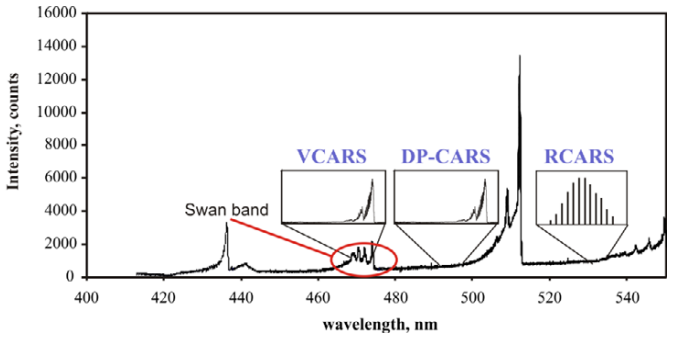

Fig. 7. Emission spectra of C_2

Combined measurements of VCARS and DP-CARS in a fuel-rich premixed C_2H_4/air flame obtained in a McKenna burner demonstrate the suitability of DP-CARS for measurements in strongly sooting flames. The frequency-doubled Nd:YAG laser (ω_1, 10Hz, 10 ns) was used as a pump beam for the CARS process with a bandwidth of 0.5 cm^{-1} and as a pump source for the two dye lasers. The narrowband dye laser (ω_2) was equipped with fluorescein dissolved in methanol with a bandwidth of 0.1 cm^{-1} and served as the second pump source. The laser was tuned to 549 nm. The broadband dye laser (ω_s) was equipped with a mixture of Rhodamine 610 and Rhodamine 640 in methanol to generate the Stokes beam at around 604 nm with a bandwidth of 170 cm^{-1} (FWHM). Using this laser combination in a USED-CARS phase matching configuration [24], the standard CARS signal was emitted at around 473 nm and the dual-pump CARS signals simultaneously at around 487 nm. Fig. 8 show both N_2 CARS spectra taken at a height of h=17mm above the burner in the sooting region of the flame for a fuel-air ratio of $\Phi = 2.3$. Clear differences between the standard VCARS and the DP-CARS spectrum can be seen. The standard VCARS spectrum is influenced by the C_2 Swan band. The evaluation leads in this case to a temperature underprediction of 160 K in comparison to the DP-CARS signal.

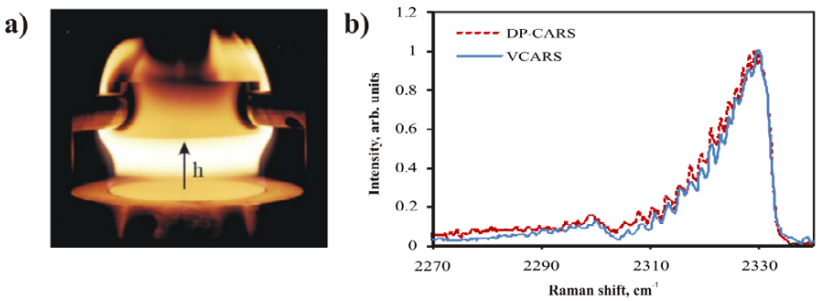

Fig. 8. Spectra taken at h=17 mm for standard VCARS and DP-CARS (b), photo of the premixed C_2H_4/air flame

For diffusion flames the situation is even worse. Here a strong, varying background from nonresonant four-wave mixing coherently interferes with the resonant DP-CARS signal. Additionally in a diffusion flame low N_2 concentrations are expected especially when taking measurements close to the core of the fuel jet. To eliminate effects from the non-resonant susceptibility, which can be severe in fuel-rich combustion zones [25], the non-resonant background was suppressed by a polarization technique. This suppression is necessary to achieve precise temperature values. The theory for the polarization dependence of dual-pump CARS has been presented by Hancock et al. [19]. By an adequate choice of polarization for the incoming laser beams different polarizations are achieved for the resonant and the nonresonant part of the CARS signal. To suppress the nonresonant background an analyzer has to be set perpendicular to the polarization of the nonresonant signal in the detection path at $\theta_A = 0°$. Polarisation angles for the three laser beams were chosen to be $\theta_1 = 45°$ for the narrowband dye laser beam ($\omega_2 = 549$ nm), $\theta_2 = 90°$ for the broadband dye laser beam ($\omega_s = 604$ nm) and $\theta_3 = 135°$ for the Nd:YAG laser beam ($\omega_1 = 532$ nm). In Fig. 9, this polarizations scheme is shown.

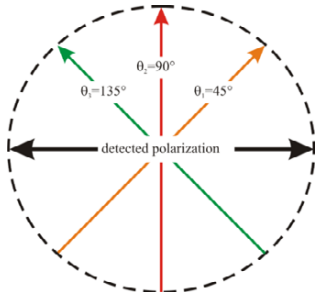

Fig. 9. Polarization scheme for the DP-CARS technique

With this set-up DP-CARS measurements were performed in a laminar C_2H_4 diffusion flame. The burner consists of two co-annular tubes for fuel and co-flow with a inner diameter of 2.2 mm and an outer diameter of 30 mm. A fuel flow of 0.075 sl/min ethylene and an air co-flow of 10 sl/min were used to establish the flame. It is shown in Fig. 10a indicating also the measurement positions. To increase the signal intensity, the maximum of the excitation spectrum of the broadband dye laser was shifted to the N_2 CARS-signal. Furthermore, 100 single shot signals were accumulated at each measurement position within the flame. Measurements were taken at heights of h=1 mm, 8 mm, 18 mm, 23 mm and 28 mm at different radial positions. The results of these temperature profiles are shown in Fig. 10. The measured spectra could be evaluated at nearly every position within flame. Only the centre region at low downstream positions, the N_2 concentration was too low.

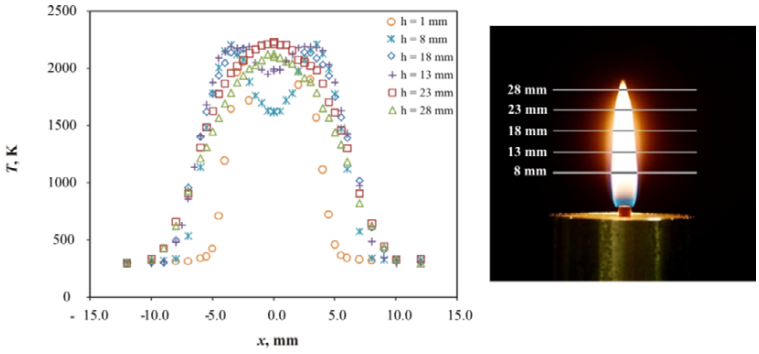

Fig. 10. Temperature profiles in different downstream positions

At 18 mm, no accurate evaluation was possible as an additional peak appeared interfering with the N_2-CARS signal. This peak may contribute to some composition products of C_2H_4 decomposition. It should be mentioned that at some positions, e.g. at a height of 18 mm near the centre of the burner, an additional coherent signal appeared in the CARS spectrum. This was correlated with a rather high soot concentration in the flame and low N_2 concentration. The coherent signal appeared at the same Raman shift (1580–1630 cm^{-1}) as the ethylene and has already been observed by Kearny et al [26]. This peak was substantially broader than the C_2H_4 peak. At some positions in the flame with rather high soot concentration, e.g., at 18 mm, this peak even prohibited accurate evaluation of the temperature because of interference with the N_2 hot band. Probably this occurred due to significant concentrations of intermediate products which have similar Raman resonances. We attribute these smeared structures to the C=C double bond of complex hydrocarbons being formed at these locations. A possibility to avoid this is to shift the wavelength of one of the narrowband beams in order to move the nitrogen signal away from the fixed spectral position of the ethylene signal. By this at least temperature measurements a still possible at these flame conditions.

6. Conclusion

In this work, we discussed the applicability as well as the limitations of the DP-CARS technique for combustiondiagnostics. This was demonstrated at ambient pressure by applying various types of flames and different fuels often used as a reference in research laboratories. Premixed, partially premixed and diffusion type flames with C_3H_8 and C_2H_4 as a fuel are used.

Simultaneous temperature and fuel-air ratio measurements were demonstrated for a C_2H_4/air flame. It was also shown that DP-CARS could be applied to complex fuels like isooctane, n-hexane, methanol or a multi-component fuel similar to gasoline. In contrast to LRS, no influence of fluorescence was noticeable. Nevertheless for fuel/air ratios near stochiometry the CARS signal intensity of the fuels relative to N_2 are low and e.g. a polarization approach might be necessary.

Also CARS spectra intermediate species like CO or H_2 could be detected by DP-CARS. H_2 concentration relative to N_2 could be measured down to 0.8% in combination with gas phase temperatures. For the evaluation of the H_2 CARS spectra a new line width model was tested. Excellent agreement between temperature evaluated from DP-CARS spectra including H_2 and results from N_2 standard VCARS thermometry were found.

The use of DP-CARS in highly sooting flames was demonstrated. In most cases not influence of the high flame luminosity or the C_2 Swan band was found. Only in a few highly sooting regions of a C_2H_4 diffusion flame interference effects do not allow a temperature evaluation with the present setup. Nevertheless it might be possible to shift the DP-CARS signal to an interference free region.

These examples show the large potential of DP-CARS to achieve reliable and precise gas phase temperature and concentration information of combustion relevant species even for challenging flame conditions.

Acknowledgement

The authors gratefully acknowledge financial support of part of the work by the German National Science Foundation (DFG) and the German Academic Exchange Service (DAAD).

References

1. A.C. Eckbreth. Comb. Sci. Techn. Book Series. 1996, Amsterdam, Niederlande, 1996.
2. R.S. Barlow, A.N. Karpetis, J.H. Frank, and J.-Y. Chen, Combust. Flame 127 (2001) 2102-2118.
3. G. Grünefeld, V. Beushausen, P. Andresen, and W. Hentschel, Appl. Phys. B 58 (1994) 333-342.
4. P.C. Miles, Applied Optics 38 (1999) 1714-1732.
5. M.C. Weikl, F. Beyrau, J. Kiefer, T. Seeger, and A. Leipertz, Opt. Lett. 31 (2006) 1-3.
6. W. Meier, R.S. Barlow, Y.-L. Chen, and J.-Y. Chen, Comb. Flame 123 (2000) 326-343.

7. S.A. Tedder, S. O'Byrne, P.M. Danehy, and A.D. Cutler.in *43rd Aerospace Sciences Meeting and Exhibit*, 2005 Reno NV: AIAA.
8. S.A. Tedder, J.L. Wheeler, A.D. Cutler, and P.M. Danehy, Appl. Opt. 49 (2010) 1305-1313.
9. M.C. Weikl, T. Seeger, R. Hierold, and A. Leipertz, J. Raman Spectrosc. 38 (2007) 983-988.
10. J. Egermann, T. Seeger, and A. Leipertz, Appl. Opt. 43 (2004) 5564-5573.
11. J. Jonuscheit, PhD Thesis, Friedrich-Alexander-Universtität Erlangen-Nürnberg, Germany, 2001.
12. W. Stricker, R. Lückerath, U. Meier, and W. Meier, J. of Raman Spectrosc. 34 (2003) 922-931.
13. F. Beyrau, A. Datta, T. Seeger, and A. Leipertz, J. Raman Spectrosc. 33 (2002) 919-924.
14. S.M. Green, P.J. Rubas, M.A. Paul, J.E. Peters, and R.P. Lucht, Appl. Opt. 37 (1998) 1690-1701.
15. R.P. Lucht, Opt. Lett. 12 (1987) 78-80.
16. P.M. Danehy, S. O'Byrne, A.D. Cutler, and C.G. Rodriguez, in *JANNAF APS/CSI/PSHS/MSS Joint Meeting*. 2003, JANNAF: Colorado Springs, USA.
17. K.C. Smyth, H.J. Miller, R.C. Dorfman, W.G. Mallard, and R.J. Santoro, Comb. Flame 62 (1985) 157-181.
18. L.A. Rahn and R.E. Palmer, J. Opt. Soc. of Am. B 3 (1986) 1164-1169.
19. R.D. Hancock, F.R. Schauer, R.P. Lucht, and R.L. Farrow, Appl. Opt. 36 (1997) 3217-3226.
20. L.A. Rahn, L.J. Zych, and P.L. Mattern, Opt. Commun. 30 (1979) 249-252.
21. L. Bonamy, H. Tran Thi Ngoc, P. Joubert, and D. Robert, Eur. Phys. J. D 31 (2004) 459-467.
22. M. Marrocco, Chem. Phys. Lett. 442 (2007) 224-227.
23. A.C. Eckbreth and R.J. Hall, Comb. Flame 36 (1979) 87-98.
24. A.C. Eckbreth, G.M. Dobbs, J.H. Stufflebeam, and P.A. Tellex, Appl. Opt. 23 (1984) 1328-1339.
25. R.J. Hall and L.R. Boedeker, Appl. Opt. 23 (1984) 1340-1346.
26. S.P. Kearney and M.N. Jackson, AIAA J. (2009) 4547-2955.